Improved Spectral Sensing in Cognitive Radios Using Photonic-Based Principal Component Analysis

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***Abstract*—We propose and experimentally demonstrate a microwave photonic system that iteratively performs principal component analysis on partially correlated, 8-channel, 13 Gbaud signals. The system that is presented is able to adapt to oscillations in interchannel correlations and follow changing principal components. The system provides advantages in bandwidth performance and fan-in scalability that are far superior to electronic counterparts. Wideband, multidimensional techniques are relevant to >10 GHz cognitive radio systems and could bring solutions for intelligent radio communications and information sensing, including spectral sensing.**

Keywords—Microwave Photonics; Analog Signal Processing; RF Photonics

I. INTRODUCTION

Principal component analysis (PCA) is a well-known technique for pattern recognition and dimensionality reduction for multidimensional random variables. It is the basis of many statistical analyses that rely on multivariate correlations [1]. We interest ourselves in the spatial correlation of multiple time series, particularly RF signals. PCA and its cousin statistical procedures, such as independent component analysis (ICA), are a fundamental part of the solution to the blind source separation (BSS) problem in RF signal processing [2], which is a useful technique for spectrum sensing in cognitive radio systems [3]. The multi-antenna system design used to solve BSS bears a fatal challenge to digital signal processing: the marriage between high bandwidth and large fan-in. The more antennas and the higher the bandwidth requirement in the system, the higher the requirements for clock speed and memory of digital processors. Microwave photonics (MWP) is the enabling technology for the processing of radio frequency (RF) signals, in particular the part of the spectrum belonging to SHF (3–30 GHz) and EHF (30–300 GHz) as classified by the International Telecommunications Union (ITU). A MWP implementation of PCA significantly relaxes the hardware constraints of digital signal processing systems.

Furthermore, microwave photonics brings additional advantages relative to electronic microwave filters, such as low loss, high bandwidth, tunability and immunity to electromagnetic interference. Because fast response times are inherent to photonics, MWP has found fruitful applications in arbitrary waveform generation, chirped microwave pulse generation, microwave differentiators and real-time operations over microwave signals [4], but few present the advantages of tunability or wavelength-division multiplexing (WDM). Recent work [5] demonstrated iterative principal component extraction of partially correlated 8-channel 1 Gbaud input. The present work extends the design in [5] to handle electronic signals up to 13 Gbaud, bringing signal processing capabilities to the SHF radio spectrum, which include wireless LAN (local area network), radar, communication satellites and television broadcasting. More importantly, WDM allows the fan-in to be as scalable as the number of channels that can be multiplexed into an optical fiber.

II. METHODS

PCA linearly transforms a set of variables ( ), with = 1,..., , into a set of principal components (PCs) devoid of second-order correlations, i.e. < ˜ > = 0 where $< . >_t$ is a time average. The present work extends the experiment design in [5] to allow for 7-dimensional control of interchannel correlations. It is very similar to a finite impulse response (FIR) microwave photonic filter (cf. [4]), but with a wavelength-dependent tunable weight bank (Fig. 1). An electric non-return-to-zero (NRZ) signal with several GHz bandwidth is constructed using a single pulse-pattern generator (PPG) carrying a programmable 8192-long bit pattern.

This signal is imprinted in 16 wavelength carriers via a Mach Zehnder modulator (MZM), producing complimentary modulations at each arm. 16 wavelengths are necessary to encode 8 channels with two polarities (positive and negative) (see Fig. 2(a)). After modulation, an equally-spaced fiber Bragg grating (FBG) array adds wavelenanosecond delayed with respec Another function of the FBG array is to select 8 wavelengths corresponding to positive or negative modulations of respective channels (Fig. 1(a): (1) and (2)). A tunable wavelength-dependent weight bank weights each channel independently and a photodetector (PD) performs the desired by carrying out optical-to-electrical conversion (Fig. 1(b): (3) and (4)).

978-1-4673-8118-5/15/$31.00/©2015 IEEE

Fig. 1. Experimental setup, adapted from [5]. (a) Input g
distributed feedback laser; AWG: arrayed-waveguide
PPG: pulse pattern generator; MZM: Mach-Zehnder m
Bragg grating. (b) WDM weighted addition where circle
attenuators, and PD: photodiode, and (c) PCA algorithm,
digital converter; CPU: central processor; DAC: digi

Having described the partially correlated, multichannel NRZ sequence as input, we proceed to describe the PCA algorithm. Its goal is to control the weight bank so that it outputs the first principal component of this multidimensional signal. In this setup, the CPU is responsible for all correlation computations, and therefore limits the control loop latency. The algorithm is divided in two steps.

First, the CPU digitizes and stores in memory each of the 8 channels waveforms by individually selecting them using the filter bank.

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(6)

In the second step, we simulate an iterative weight control algorithm called the normalized Hebbian learning rule, described in eq. (6) [7, 5]. The algorithm only requires a sample of the output waveform after weighted addition—which is carried out by the ADC with a time window corresponding to 2000 bits—and its correlations with the stored waveforms samples. After a finite number of iterations, μ_1 in eq. (6) converges successfully to the first PC. In this experiment, the iteration count was limited to 40, when the converged weight value is compared with the PC computed by the SVD method. The extension of this algorithm to the computation of all PCs is described in [5].

In [5], electronic non-idealities caused the accuracy of the PCA algorithm to suffer under certain conditions. As an example, one RF amplifier (not shown in Fig. 1) was band limited to 1.3 GHz. Impedance mismatch was also present in the circuit, introducing overshoot and ringing. These obstacles

Fig. 3. Accuracy analysis of 290 runs of the experim Histogram relating the accuracy p (square of dot product b measured PC weight vector) and R ratio between t eigenvalues. The histogram was binned according to qui contains many different Markov memory functions mapp of R. The experimental PCA task accurately ($p > 0.9$) co weight for $R > 1.2$, which translates to the first PC bei defined" than the second PC. Low accuracy can be e convergence or convergence to the wrong PC. (b) 51 wei in the rightmost bin (darker blue) of the histogram in (a). highlighted for clarity. The weight vectors were plotted o that highlights the spatial diversity of the explored weight different Markov parameters.

The necessary key to reveal each of the dimensional RF signal is a weight vector Finding this key is the fundamental objectiv correlation changes, the key changes. In generated an unbiased binary additive Mark seventh order ($m = 7$), as described in e memory function used to create such a temporarily access the spectrum until a licensed user is detected or until network quality degrades below a application